Pultrusion Process Development for Long Space Boom Model

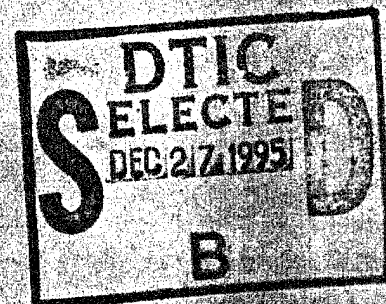DTIC
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Maywood L. Wilson and Robert Miserentino

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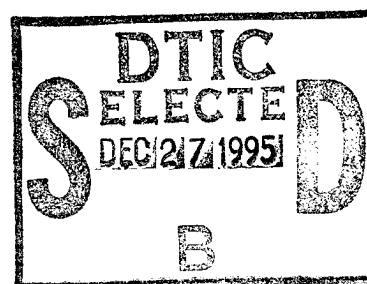
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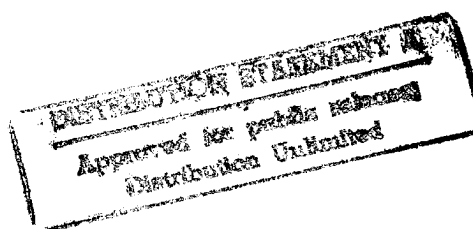# Pultrusion Process Development for Long Space Boom Model

Maywood L. Wilson and Robert Miserentino

Langley Research Center
Hampton, Virginia

NASA

National Aeronautics
and Space Administration

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Information Division

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Abstract

Long flexible-boom models were required to develop ground-vibration test methods for very-low-frequency space structures with applications to the proposed Space Station. Pultruded quasi-isotropic composite beams were selected as an option over extruded aluminum alloy structures because of the lower cost potential, the higher specific strength, the flexural properties, and the dynamic similarity considerations. The reinforcement material that was used was biaxial [0°/90°] fiberglass roving held in place with knitted polyester yarn such that equal fiber volume in 0° and 90° orientations provided nearly equal strength in both longitudinal and transverse directions. An isophthalic polyester resin system was used as the matrix. Continuous lengths up to 270 ft were easily pultruded with biaxial fabric. Tracking problems were encountered with similar unidirectional fabrics. The analyses of processing problems were conducted to determine causes for delamination, scaling, and sloughing. Ultrasonic C-scanning, scanning electron microscope (SEM) examinations, and mechanical testing to failure were conducted. A comparison is made of four different pultrusions with varied matrices and fiber orientations. Test results indicate that the pultrusion process can be used to produce quasi-isotropic composite structures by selective fiber orientation using the knit-locked fabric concept.

Introduction

Pultrusion is not a new process, it was initiated in the early 1950's. (See ref. 1.) It is, however, still in its infancy in the aerospace industry. The NASA Langley Research Center (LaRC) in Hampton, Virginia, and the U.S. Army Materials and Mechanics Research Center (AMMRC) in Watertown, Massachusetts, are the only government facilities that have in-house pultrusion laboratories with ongoing research and development in pultrusion materials and processes. Experiments are being conducted at LaRC for pultrusion in advanced-composites technology with applications to aeronautical and space structures. In one such program, long flexible beams were needed to establish ground-vibration test methods for very-low-frequency structures. The beams were rectangular in cross section, 0.250 in. in thickness, 4.000 in. in width, and 32.81 ft in length; the beams weighed 25.6 lb each. In figure 1, suspended beams are shown undergoing dynamic tests.

The composite reinforcement materials approach used in the beam models was unique in that potentially equal strength is provided in the longitudinal [0°] and transverse [90°] directions. (See ref. 2.) The availability of this new type of fabric makes possible the pultrusion fabrication of quasi-isotropic composite materials using the conventional "wet resin" technique. To achieve transverse strength in the past, preimpregnated tapes, continuous strand mats, or woven cloths were used in pultrusion. Quasi-isotropy can also be achieved in circular profiles by filament overwinding techniques. (See ref. 3.) The use of mats to impart transverse strength into a pultrusion results in low strength values. (See ref. 2.) Reference 4 is one of the few documents available on preimpregnated tape pultrusion techniques.

Fabrication Method and Materials

The continuous-reinforcement pultrusion method was used to produce the beams at a rate of 1 ft per minute. Rolls of the reinforcement materials were mounted on a creel and pulled through a resin bath. Each ply was separated by holddown spreader bars as it traveled through the resin system. (See fig. 2.) Approximately 1741 ft of material was pultruded in nine runs for this project. The cure die was machined from 17-4 PH (precipitation-hardened) stainless-steel, heat-treated to Rockwell C-45, and surface-finished to 9×10^{-6} in. root mean square (rms). Electrical strip heaters were used to heat the die, and thermocouples were used to monitor and control die heat zones. (See fig. 3.) The die cross-section dimensions were constant, and its length was 30 in. Die-temperature profiles of runs 22583-5, 82483-9, and 111380 with matrices of resin systems 1, 2, and 3 (table I), respectively, are shown in figure 4. The die station with the start-up winch attached is shown in figure 5.

The initial resin system (resin system 1) had been successfully used with smaller profiles. This system was selected because of its long catalyzed shelf life, 30 days at 72°F. However, the catalyst and filler caused problems of scaling, cracking, sloughing, and delamination. Attempts to correct these anomalies by shifting the die heat zones were unsuccessful, and after five runs this resin system was replaced by resin system 2. Resin system 3 was used to pultrude unidirectional fiberglass roving reinforced material for comparison purposes.

A commercially available fiberglass fabric called COFAB[1] was selected for the reinforcement. This

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[1] Trademark of Gulf States Paper Corporation.

material consists of fiberglass (electrical grade, E fabric glass) rovings locked together by a knitted polyester yarn to form a stable cloth-like fabric. (See figs. 6 and 7.) This material is available in orientations of [0°], [90°], [0°/90°], and [±45°] directions. Seven pultrusion runs were made with fiber orientation combinations of [0°] and [0°/90°] plies, and two runs were made with all [0°/90°] orientations.

Processing Problems

Processing problems encountered were surface roughness, scaling, sloughing, cracking, voids, delaminations, and tapered edges. Sections of three pultrusion runs depicting surface and delamination problems (top specimen), tapered edges (center), and the developed process (bottom) are shown in figure 8. The problems were divided into the following three groups for analysis and correction: (1) resin system, (2) reinforcement material, and (3) cure cycle. Resin-related problems were surface roughness, scaling, sloughing, cracking, and delaminations. These problems were eliminated, with the exception of some scaling, by changing to resin system 2. Thermal analysis using a Dupont 1090 differential scanning calorimeter (fig. 9) shows that resin system 1 has a single catalyst with one exothermic peak and a short reaction range, whereas system 2 has a double catalyst, two exothermic peaks, and a broader reaction range. The latter system is indicative of a less violent, lower rate of reaction, which allows the resin to cure more uniformly from the center outward to the surfaces. This uniform curing process accounts for some of the process improvements made by resin system 2. The probable cause of excessive voids and delaminations in the pultrusions using resin system 1 was free moisture produced by the alumina trihydrate when it was heated to processing temperatures. Some improvements in the surface finish were achieved by adding Nexus[2] polyester surfacing veil style 131-10. Finally, after adjusting the die exit temperature below 240°F by installing a water-cooling unit (fig. 3) over the last 4 in. of the die, scaling was completely eliminated and an excellent surface finish was produced. A die-temperature profile of the developed process (82483-9/Resin 2) is shown in figure 4.

There were two reinforcement problems: (1) a tracking problem with the unidirectional [0°] knit-locked fabric and (2) tapered edges caused by the biaxial [0°/90°] material having been cut slightly undersize in width. The tracking problem was solved by changing to all [0°/90°] biaxial reinforcement material, and the tapered-edge problem was solved

by adding [0°] roving. The final reinforcement layup consisted of two plies of Nexus veil; 11 plies of [0°/90°] biaxial COFAB, 18 oz/yd^2; two rovings 30 K (see ref. 1), 112.5 yd/lb yield for each [0°/90°] biaxial ply (one such roving applied to each outside edge); and two plies of Nexus veil, style 131-10 (fig. 10).

Tests and Results

A comparison is made of cost and properties of extruded 6061-T6 aluminum alloy (ref. 5) and the fiberglass-reinforced pultruded models in table II. The pultruded model weighs 34 percent less, and is 28 percent higher in tensile strength. Its specific strength is two times greater than 6061-T6, and its estimated cost to produce is 3 percent greater than that of 6061-T6.

Identical tests were conducted on samples sectioned from pultrusion runs 82483-9, the final developed beam model (fig. 11); 22583-5, a beam-model run made during the development stage; 111380, which contains all unidirectional roving with cross-sectional dimensions of 0.125 in. thick by 1.0 in. wide; and a commercially produced 6-in. H-beam. Physical and mechanical tests results are listed in table III. Fiber volume and weight percent determinations were made by gravimetric analysis. Tensile, flexural, and short-beam shear tests were based on American Society for Testing and Materials (ASTM) Standards D638, D790, and D2344, respectively. These tests were conducted on an Instron testing machine[3] Ultrasonic C-scan and Scanning Electron Microscope (SEM) evaluations supported physical and mechanical test results. C-scan test results (figs. 12 to 16) show the following order of quality: (1) 111380, (2) 82483-9, (3) 6-in. H-beam web, (4) 6-in. H-beam flange, and (5) 22583-5. In the photographs, black indicates good quality and white indicates poor quality. The unidirectional roving pultrusion (fig. 12, 1-in-wide strips with white tabs) appears to transmit the highest volume of sound (black), which is indicative of the lowest void content, better fiber wetting, a higher degree of resin-fiber interface bonding, and an absence of delaminations. Scanning Electron Microscope photographs (figs. 17 to 20) show that 111380 (fig. 17) has the best fiber wetting, followed by 82483-9 (fig. 18), 22583-5 (fig. 19(a)), and the H-beam (fig. 20(a)). Internal microcracks and excessive voids in the polished cross section of 22583-5 are shown in figure 19(b). Internal microcracks in the polished cross section of the H-beam are shown in figure 20(b).

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[2] Trademark of Burlington Industries, Inc.

[3] Manufactured by Instron Engineering Corp.

Concluding Remarks

This report describes the fabrication method and materials used, identifies processing problems and corrections, presents physical and mechanical evaluation results, and relates cost data for pultrusion of long flexible beam models. These model beams were used to develop ground dynamic test methods for very-low-frequency space structures. Test results indicate that the pultrusion process can be used to produce quasi-isotropic composite structures by selective fiber orientation using the knit-locked fabric concept.

NASA Langley Research Center
Hampton, VA 23665-5225
November 5, 1987

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5. *Aluminum Standards & Data, Third ed.* Aluminum Assoc., Jan. 1972. (Supersedes Second ed. 1970-71, Issued Dec. 1969.)

Table I. Pultrusion Resin Systems

Constituent	Concentration, pph	Resin system		
		1	2	3
AROPOL^a 7241 resin, polyester	100.0	•		
AROPOL^a 7430 resin, polyester	100.0		•	
AROPOL^a 7240 resin, polyester	100.0			•
Alumina trihydrate (filler)	10.0	•		
Alumina silicate powder (filler)	10.0		•	•
Molgard^b X (internal release)	1.0	•	•	•
Microthene^c (internal release)	0.75		•	
Trigonox^d 29-B75 (catalyst)	1.3	•		
Percodox^d 16N (catalyst)	0.50		•	
Tertiary-butyl perbenzoate (TBPB) (catalyst)	0.30		•	
Benzoyl peroxide (catalyst)	2.5			•
Blue pigment	1.5			•

^{a}Trademark of Ashland Oil, Inc.
^{b}Trademark of Ram Chemicals Div., Whittaker Corp.
^{c}Trademark of U.S. Industrial Chemicals Co.
^{d}Registered trademark of Noury Chemical Co.

Table II. Comparison of Aluminum 6061-T6 and Fiberglass-Reinforced Models

	Extruded 6061-T6	Pultruded 82483-9
Density, lb/in^3	0.098	0.065
Tensile str., ksi	38	53
Specific tensile strength, in.	0.4×10^6	0.8×10^6
Weight, lb/boom	38.6	25.6
Weight, lb/ft	1.18	0.78
Cost/lb	$1.36	$2.12
Cost/ft	$1.61	$1.66
Cost, 1741 ft	^{a}$2794	^{b}$2884

^{a}Reynolds Aluminum Co. 1984.
^{b}Materials, labor, 20 percent overhead.

Table III. Comparison of Physical and Mechanical Properties[a] of Fiberglass-Reinforced Pultrusions

Property	Run 82483-9	Run 22583-5	Run 111380	Sectioned 6-in. H-beam	
Reinforcement type and fiber orientation	Roving 2-Nexus 11-0°/90° 2-Nexus	Roving [0°, 0°/90°, 0°, 0°/90°, 0°]s (80% 0°)	Roving 0°	Continuous strand mat	
Resin system	2, AROPOL 7430 polyester[b]	1, AROPOL 7241 polyester[b]	3, AROPOL 7240 polyester[b]	Commercial polyester	
				Flange	Web
Density, lb/in^3	0.065	0.060	0.067	0.057	0.058
Fiber volume, percent	44	38	50	28	29
Fiber weight, percent	62	57	68	44	49
Tensile strength: 0°, ksi 90°, ksi	53 32	42 14	108	29	27 8
Flexural strength: 0°, ksi 90°, ksi	46 43	43 21	161	55	44 17
Flexural modulus: 0°, Msi 90°, Msi	2.0 2.1	2.3 0.7	5.0	1.9	1.9 .9
Short-beam shear: 0°, ksi 90°, ksi	5 5	6 2	9 1	6 3	
Specific tensile strength: 0°, in. 90°, in.	0.8×10^6 $.5 \times 10^6$	0.7×10^6 $.2 \times 10^6$	1.6×10^6	0.5×10^6	0.5×10^6 $.1 \times 10^6$

[a]All mechanical properties tests were conducted at room temperature.
[b]From table I.
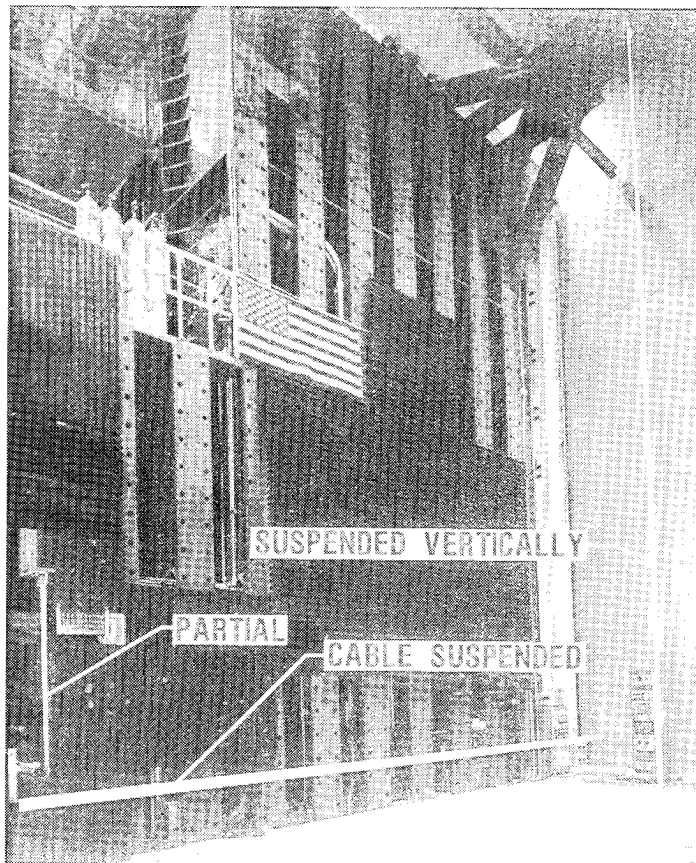
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Figure 1. Dynamic tests of boom models.

Fiber creel   Resin tank   Preform dies   Cure die   Puller
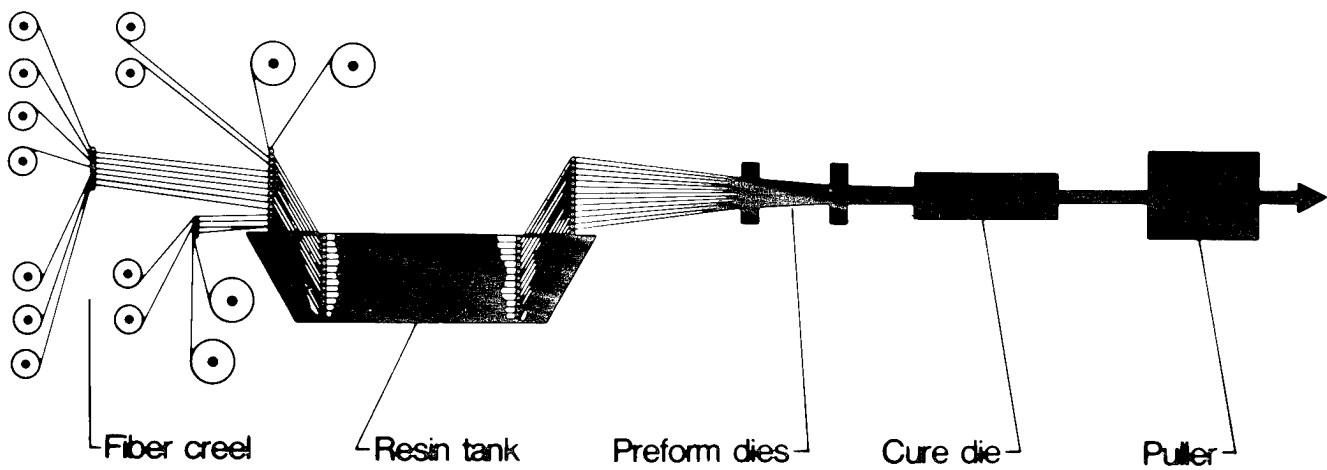
Figure 2. Pultrusion process.
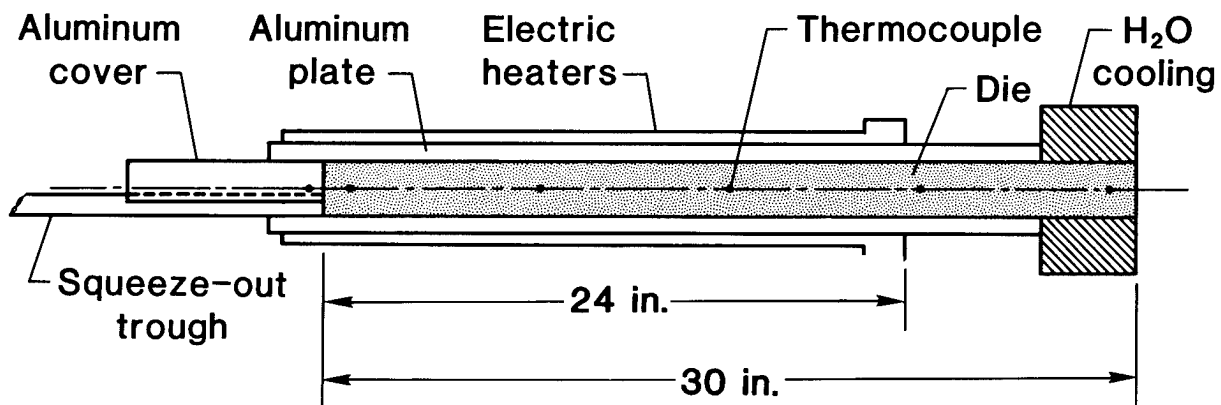
Figure 3. Profile view of pultrusion die.
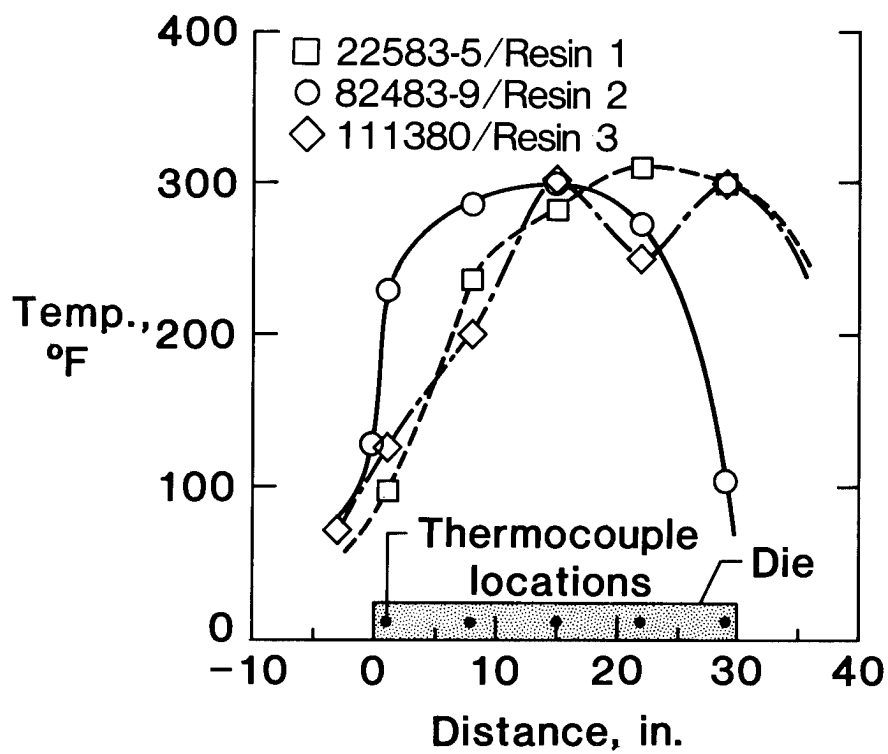
Figure 4. Die-temperature profiles of pultrusion processes.
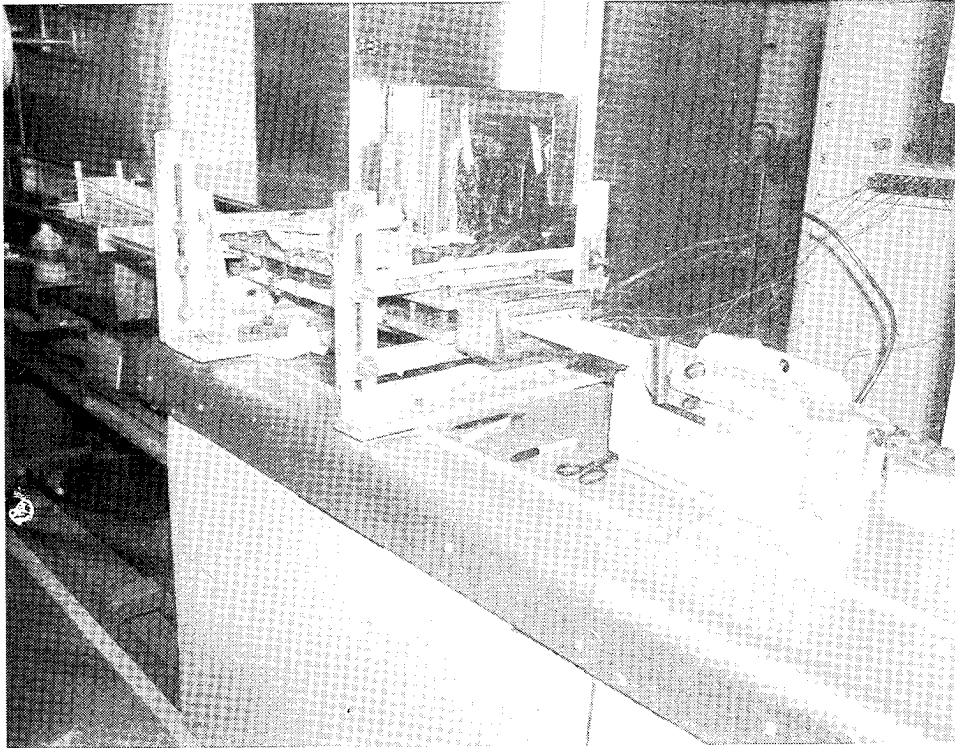
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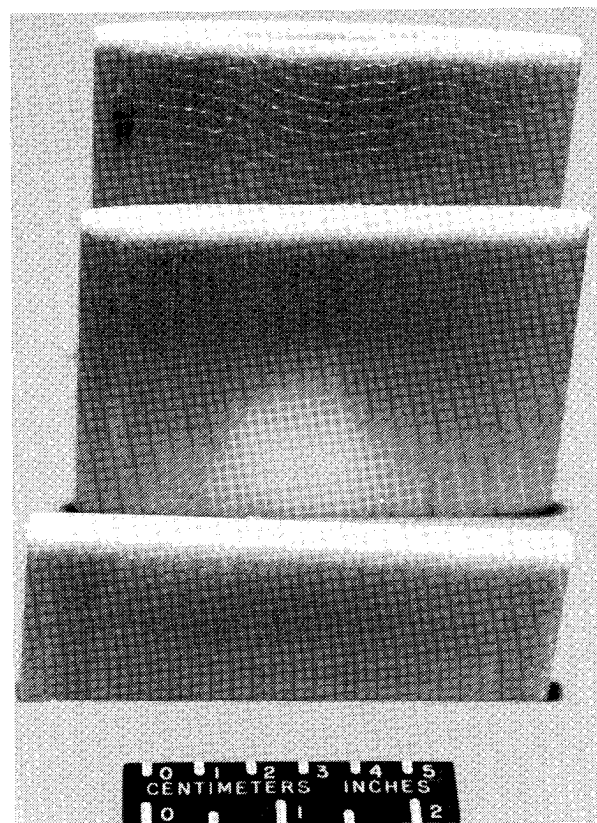Figure 5. Die station showing start-up mechanism.
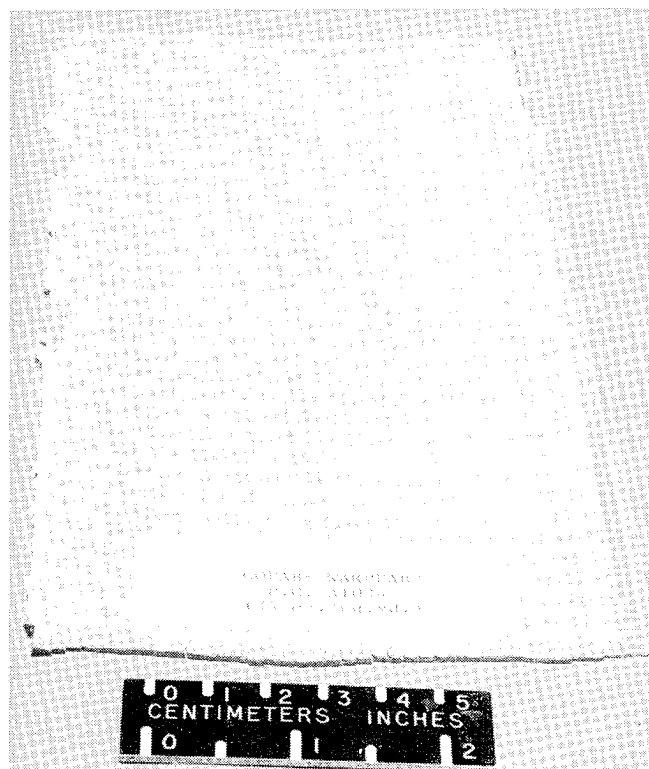
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Figure 6. Unidirectional material, knit-locked fiberglass.
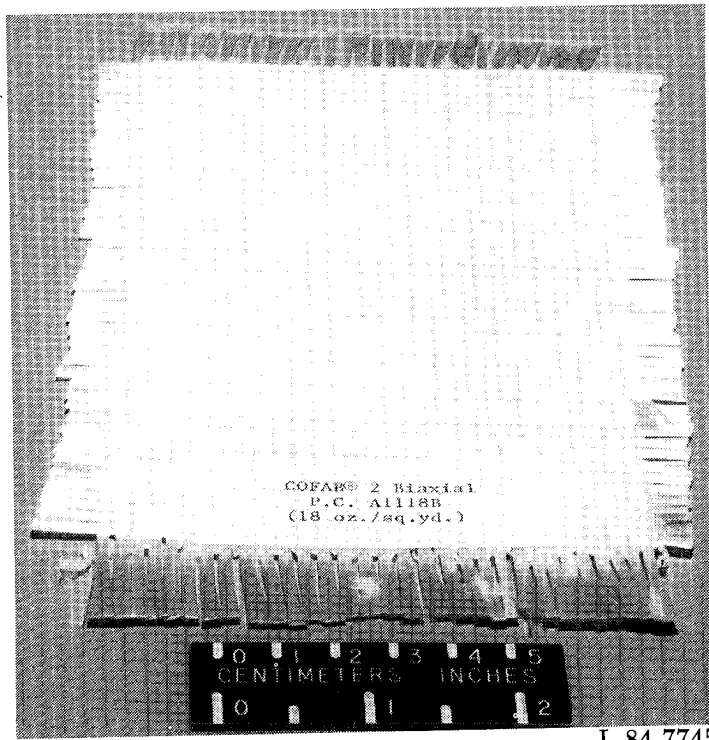
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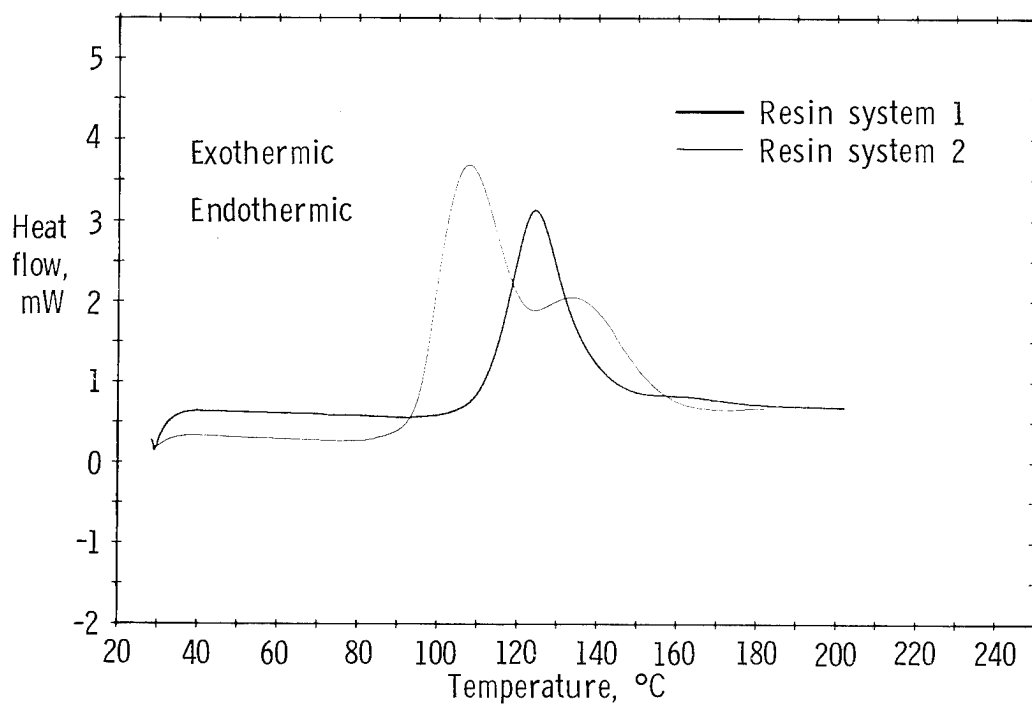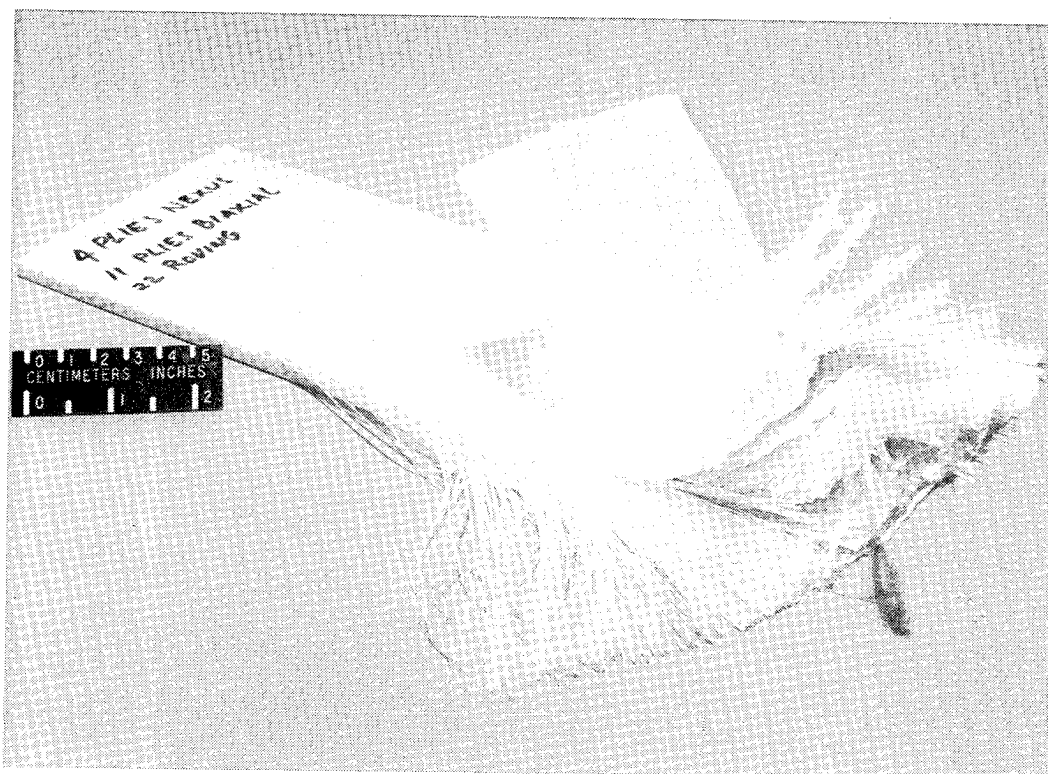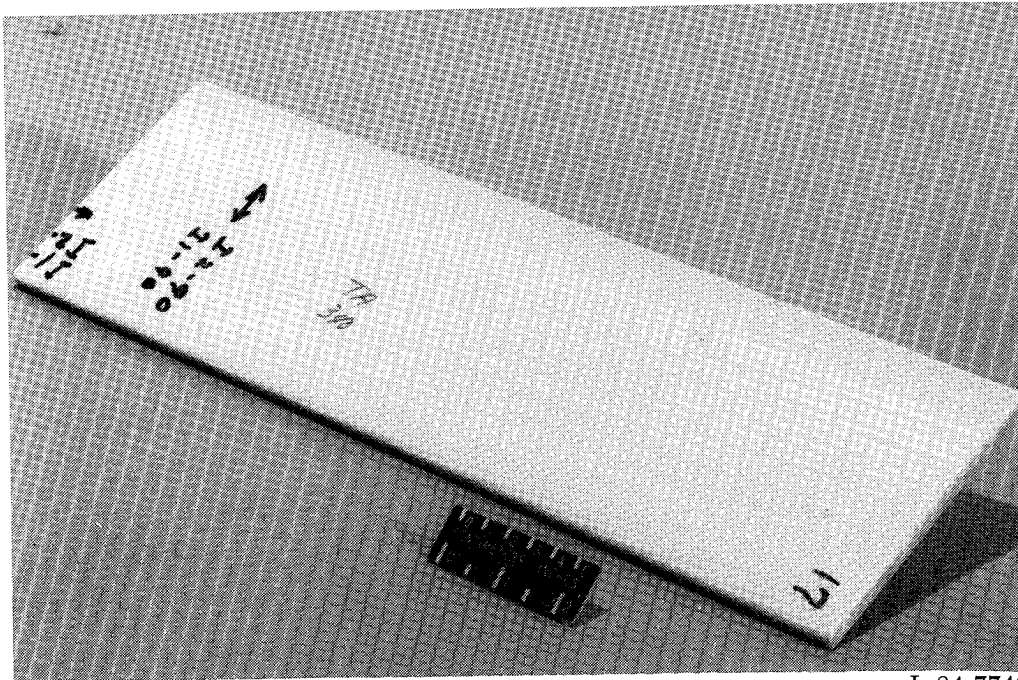Figure 7. Biaxial material, knit-locked fiberglass.

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Figure 8. Sectioned pultrusions showing defects.

Figure 9. Differential scanning calorimeter (DSC) thermogram of polyester resins.

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Figure 10. Start-up end of pultrusion run.

L-84-7746

Figure 11. Section of pultrusion run 82483-9.
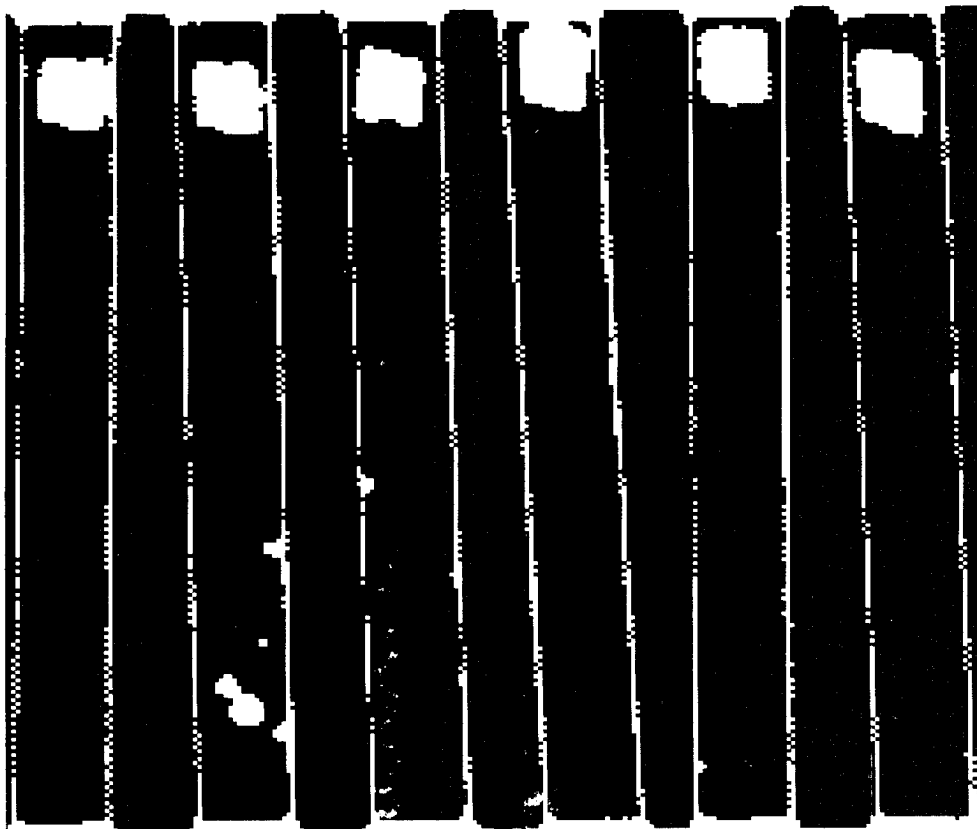
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Figure 12. C-scan of pultrusion run 111380.

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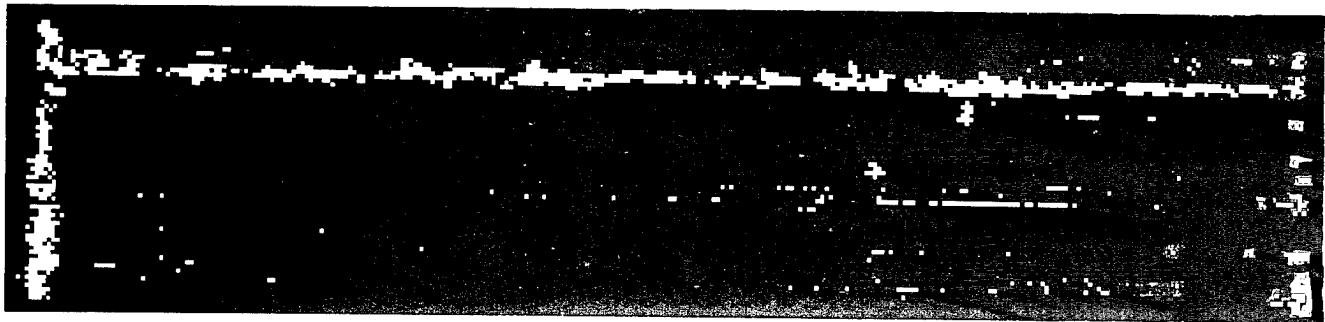
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Figure 13. C-scan of pultrusion run 82483-9.
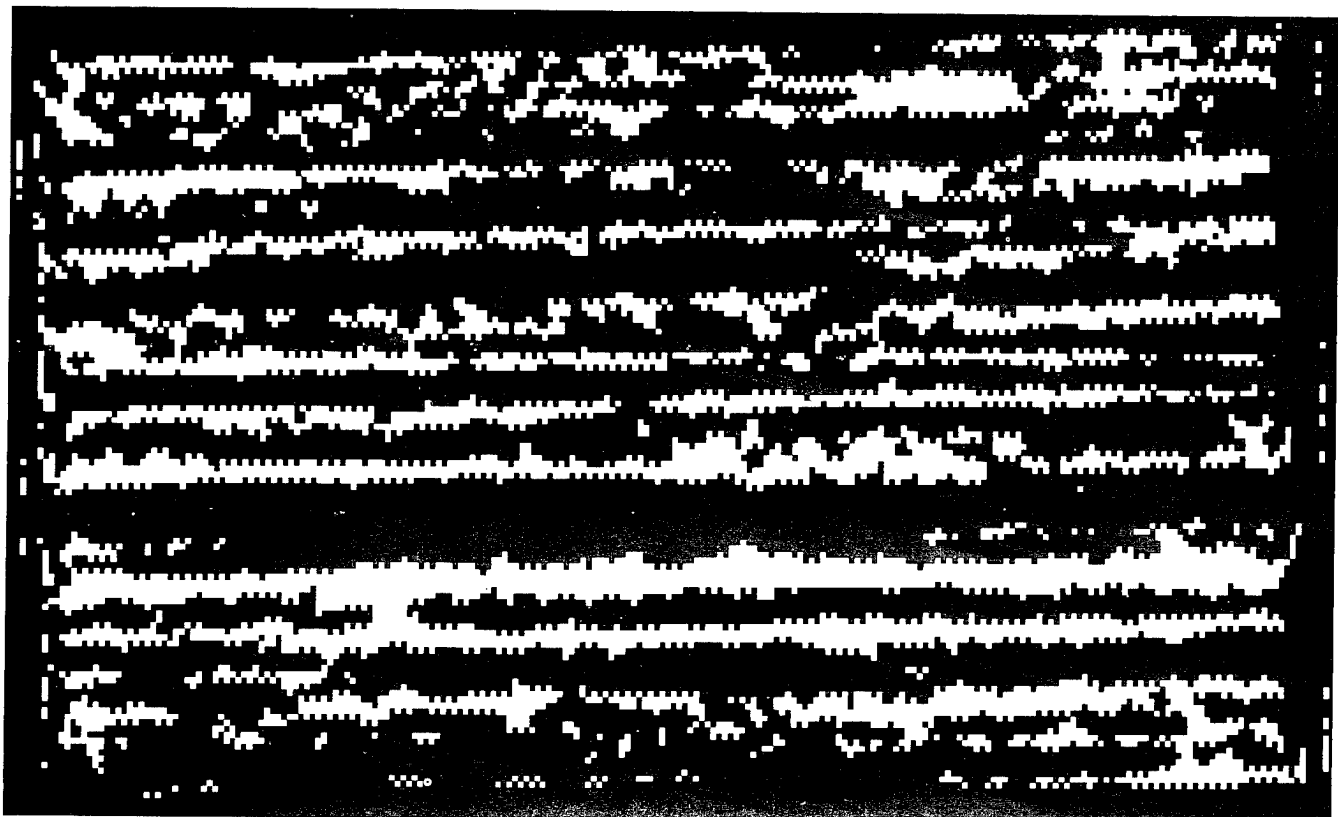
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Figure 14. C-scan of sample from pultruded H-beam web.
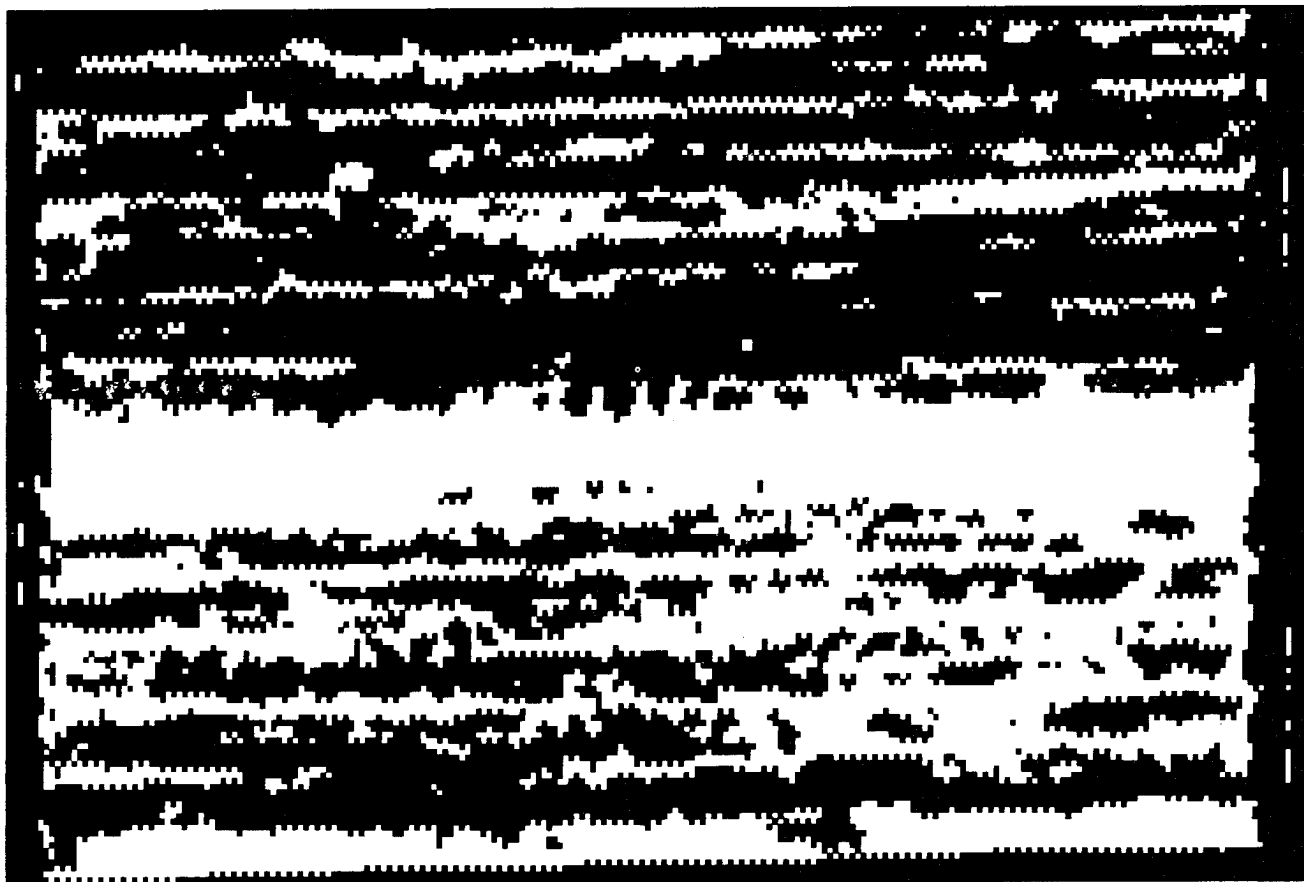
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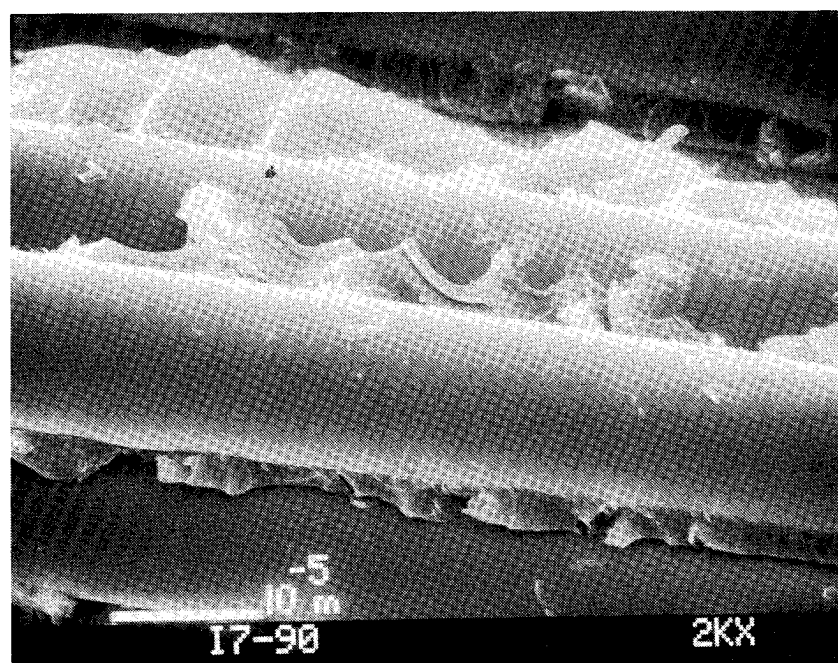
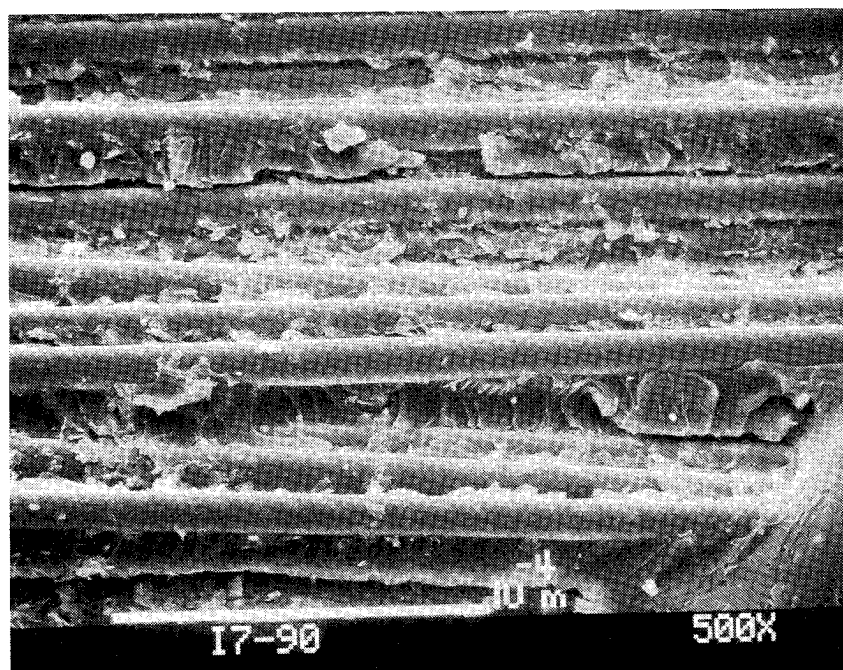Figure 15. C-scan of sample from pultruded H-beam flange.
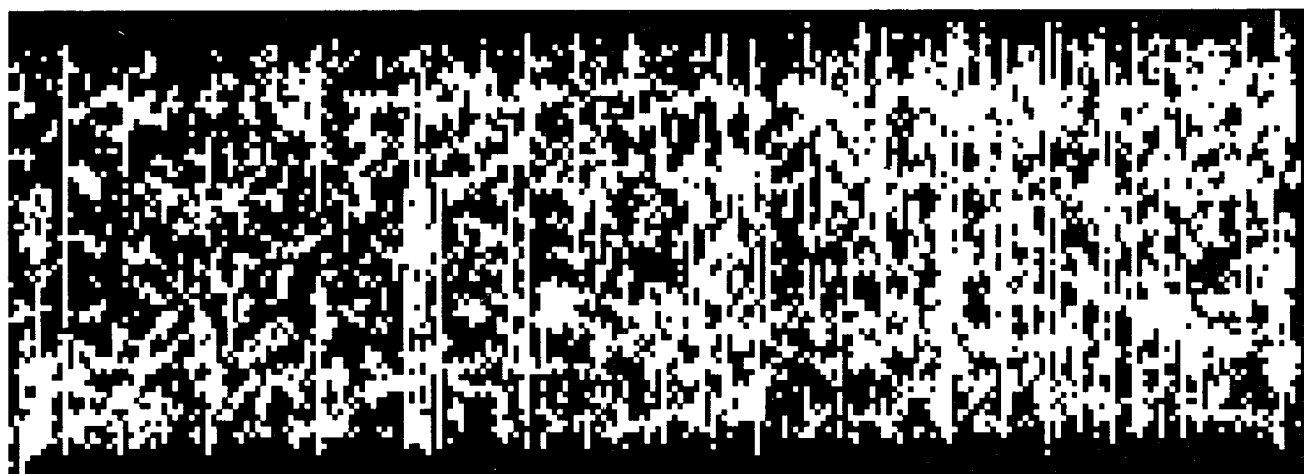
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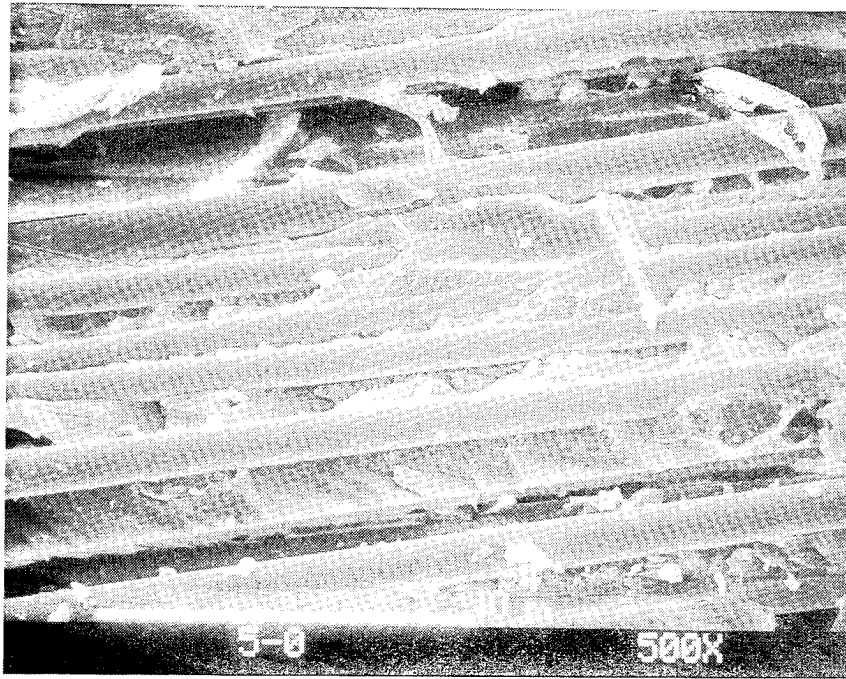
Figure 16. C-scan of pultrusion run 22583-5.

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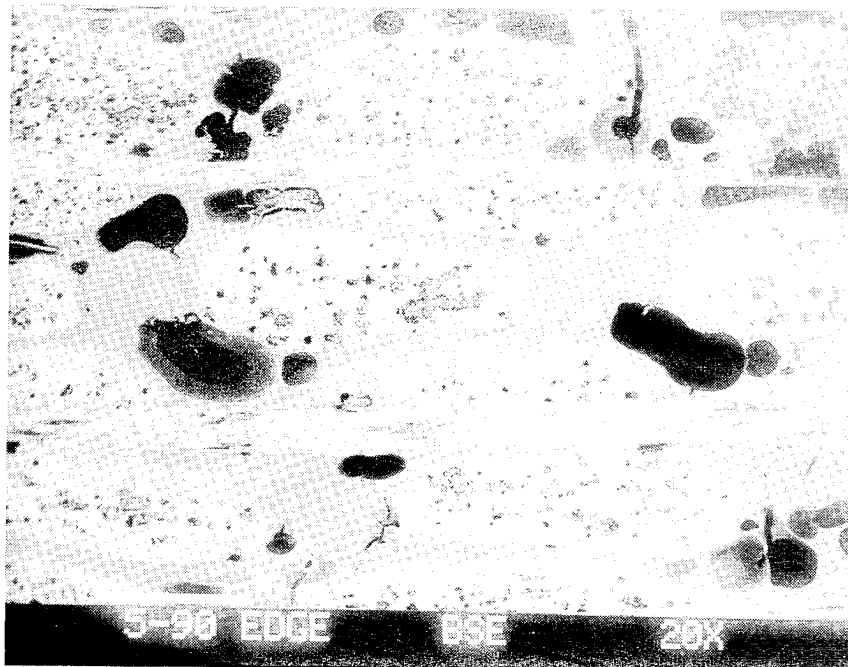Figure 17. Photomicrographs of fracture-face samples from pultrusion run 111380.

L-87-666

Figure 18. Photomicrographs of fracture-face samples from pultrusion run 82483-9.

(a) Fracture face.

(b) Cross section.

Figure 19. Photomicrographs of samples from pultrusion run 22583-5.